Dark Matter Constraints on Gaugino/Higgsino Masses in Split Supersymmetry and Their Implications at Colliders

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In split supersymmetry, gauginos and Higgsinos are the only supersymmetric particles which are possibly accessible at foreseeable colliders. While the direct experimental searches, such as LEP and Tevatron experiments, gave robust lower bounds on the masses of these particles, the cosmic dark matter can give some upper bounds and thus have important implications for the searches at future colliders. In this work we scrutinize such dark matter constraints and show the allowed mass range for charginos and neutralinos (the mass eigenstates of gauginos and Higgsinos). We find that the lightest chargino must be lighter than about 1 TeV under the popular assumption $M_1 = M_2/2$ and about 2 or 3 TeV in other cases. The corresponding production rates of the lightest chargino at the CERN Large Hadron Collider (LHC) and the International Linear Colldier (ILC) are also shown. While in some parts of the allowed region the chargino pair production rate can be larger than 1 pb at LHC and 100 fb at the ILC, other parts of the region correspond to very small production rates and thus there is no guarantee to find the charginos of split supersymmetry at future colliders.

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I. INTRODUCTION

Given the importance of supersymmetry in both particle physics and string theory, searching for supersymmetry seems to be a crucial task in the ongoing and forthcoming colliders. The forthcoming LHC collider would be able to explore the supersymmetric particles up to a few TeV and the ILC collider would allow precision test of supersymmetry. Of course, there is no guarantee to find supersymmetry at these collders since the masses of the supersymmetric particles are basically unknown. As is well known, in order to solve the fine-tuning problem in particle theory, the supersymmetric particles should be below TeV scale and thus the LHC would be a factory of supersymmetric particles. However, in the recently proposed split supersymmetry [1], the supersymmetric solution of fine-tuning problem in particle physics is given up (inspired by the need of fine-tuning for the cosmological constant), while the virtues of supersymmetry in preserving grand unification as well as providing the cosmic dark matter candidate are still retained. As a result, the mass scale of all sfermions as well as the several heavy Higgs bosons can be very high while the gaugino/Higgsino mass scale may be still below the TeV scale. While the split supersymmetry has the obvious virtue of naturally avoiding the notorious supersymmetric flavor problem, it predicts that no supersymmetric scalar particles except a light Higgs boson are accessible at the foreseeable particle colliders. Thus, if split supersymmetry is the true story [1], the only way to reveal supersymmetry at the colliders is through gaugino or Higgsino productions.

Among the gauginos and Higgsinos, the gluino is the only colored particle and thus may be most copiously produced in the gluon-rich environment of the LHC. However, the gluino is usually speculated to be much heavier than other gauginos and Higgsinos. It was shown [3] that the grand unification requirement can allow a gluino as heavy as 18 TeV. Furthermore, if the dark matter is assumed to be the gravitino produced from the late decay of the meta-stable gluino which freezed out at the early universe, it was found [4] that the gluino must be heavier than about 14 TeV and thus impossibly accessible at the LHC. So, to explore split supersymmetry we should not focus only on gluino productions; the productions of the electroweakly interacting gauginos and Higgsinos (which mix into two charged particles called charginos and four neutral particles called neutralinos) should also be considered although their production rates at the LHC are much lower. Of course, if the LHC can discover supersymmetry and then the ILC takes the task of precision test, the productions of charginos and neutralinos at the ILC will play the dominant role. For both the

[1]Some studies [2] showed that split supersymmetry is quite natural from the top-down view.

LHC and the ILC, the production of charginos will give good signatures since the subsequent decays yield energetic leptons. To facilitate the collider searches for the charginos and neutralinos, the pre-estimation of their allowed mass regions are important.

While the direct experimental searches, such as LEP and Tevatron experiments, gave robust lower bounds for the masses of charginos and neutralinos, the cosmic dark matter can give some upper bounds and thus have important implications for the searches at future colliders. Therefore, although the consequence of split supersymmetry in the dark matter issue has been considered to some extent in the literature [3–6], we in this work scrutinize the dark matter constraints on the masses of charginos and neutralinos and evaluate the corresponding production rates at the LHC and ILC.

This work is organized in the follows. In Sec. II we recapitulate the parameter space of the sector of charginos and neutralinos. In Sec. III we examine the dark matter constraints. We will show the constraints on (a) the original parameter space, (b) the masses of charginos and neutralinos, and (c) the production rates at the LHC and the ILC. The conclusions are given in Sec. IV.

Note that for the supersymmetry parameters we adopt the notation in Ref. [7]. We work in the framework of the Minimal Supersymmetric Model (MSSM) and assume the lightest supersymmetric particle is the lightest neutralino, which solely makes up the cosmic dark matter. Also, we fix the parameter $\tan\beta = 40$ since a large value of $\tan\beta$ is favored by current experiments and, in the region of large $\tan\beta (\gtrsim 10)$, our results are not sensitive to $\tan\beta$.

II. PARAMETER SPACE OF CHARGINOS AND NEUTRALINOS

The chargino mass matrix is given by

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}, \tag{2.1}$$

and the neutralino mass matrix is given by

$$\begin{pmatrix} M_1 & 0 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta \\ 0 & M_2 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta \\ -m_Z \sin\theta_W \cos\beta & m_Z \cos\theta_W \cos\beta & 0 & -\mu \\ m_Z \sin\theta_W \sin\beta & -m_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}, \tag{2.2}$$

where M_1 and M_2 are respectively the $U(1)$ and $SU(2)$ gaugino mass parameters, μ is the mass parameter in the mixing term $-\mu\epsilon_{ij} H_1^i H_2^j$ in the superpotential, and $\tan\beta \equiv v_2/v_1$ is ratio of the vacuum expectation values of the two Higgs doublets. The diagonalization of (2.1) gives two charginos $\chi^+_{1,2}$ with the convention $M_{\chi_1^+} < M_{\chi_2^+}$; while the diagonalization of (2.2) gives four neutralinos $\chi^0_{1,2,3,4}$ with the convention $M_{\chi_1^0} < M_{\chi_2^0} < M_{\chi_3^0} < M_{\chi_4^0}$. So the masses and mixings of charginos and neutralinos are determined by four parameters: M_1, M_2, μ and $\tan\beta$.

The current constraints [8] on these parameters are divided into two classes: (1) direct constraints from experimental searches of supersymmetric particles; (2) indirect constraints from some precisely measured low-energy processes or physical quantities via supersymmetric quantum effects. For split supersymmetry, almost all indirect constraints from low-energy processes, such as various B-decays, drop out since the supersymmetric loop effects in these processes usually involve sfermions which are superheavy in split supersymmetry. The most stringent direct bounds are from LEP experiments [9]: (i) the lighter chargino χ_1^+ must be heavier than about 103 GeV; (ii) the LSP must be heavier than about 47 GeV; (iii) the value of $\tan\beta$ must be larger than 2.

Note that in addition to the direct lower bound from LEP II, theoretically a large $\tan\beta$ helps to push up the lightest Higgs boson mass and thus ameliorate the stress between the experimental lower bound and the theoretical upper bound on the lightest Higgs boson mass [2]. So in our analyses we assume a large $\tan\beta$ and fix it to be 40. We checked that in the region of large $\tan\beta (\gtrsim 10)$, our results are not sensitive to $\tan\beta$.

We assume the cosmic dark matter is solely composed of the LSP, which is assumed to be the lightest neutralino χ_1^0. (If the gravitino is assumed to be the LSP and make up the dark matter, it will incur some severe cosmoligical constraints [11].)

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[2]The upper mass limit of the lightest Higgs boson is relaxed to about 150 GeV in split supersymmetry [1]. However, if the right-handed neutrinos are introduced into split supersymmetry with see-saw mechanism, the large neutrino Yukaka couplings can lower the lightest Higgs boson mass by a few tens of GeV [10].

The thermal relic density of the lightest neutralino from the freeze-out can be calculated from the Boltzmann equation which involves the thermal averaged cross section of neutralino annihilations. In our work we use the package DarkSUSY [12] and we checked that the package micrOMEGAs [13] gives the similar results in our study. In calculating the cross section of neutralino annihilations, many additional supersymmetric parameters are involved, among which the most important ones are sfermion masses and M_A (the mass of CP-odd Higgs boson). Since we focus only on split supersymmetry, all sfermion masses and M_A are superheavy. So any diagrams involving a sfermion or a heavy Higgs boson makes negligible contributions to neutralino annihilations. Actually, we found that as long as the sfermion mass or M_A gets heavier than about 10 TeV, the effects of sfermions or heavy Higgs bosons decouple, as shown in Figs. 1 and 2. The peak in Fig.1(b) happens around the 'A-funnel' resonance point $M_A \approx 2M_{\chi_1^0}$.

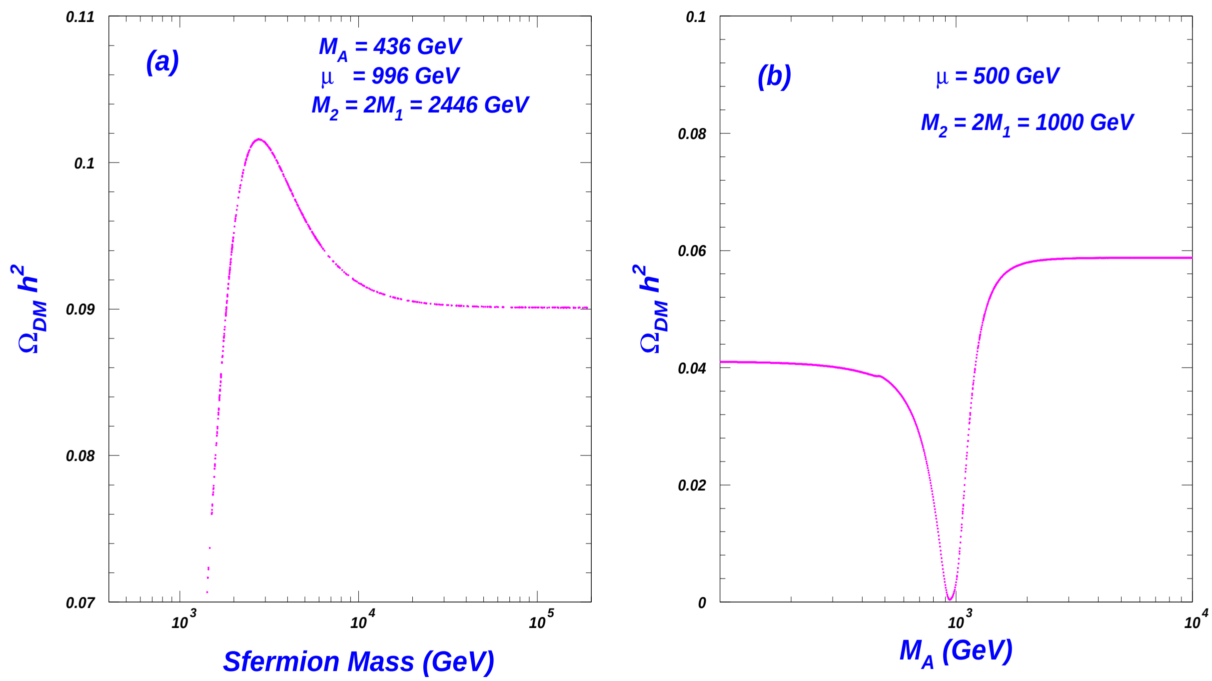

FIG. 1. The neutralino relic density versus (a) sfermon mass; (b) M_A.

III. WMAP DARK MATTER CONSTRAINTS

The 2σ allowed region for the dark matter relic density is

$$0.094 < \Omega_{CDM} h^2 < 0.129, \tag{3.1}$$

which can be inferred from the Wilkinson Microwave Anisotropy Probe (WMAP) measurements [14]. In the following we present the 2σ allowed regions for four cases: (1) $M_1 = M_2/2$; (2) μ is superheavy; (3) M_2 is superheavy; and (4) M_1 is superheavy. In our calculations we fix a 'superheavy' mass to be 100 TeV since it is high enough for the relevant supersymmetric particles to decouple from the neutralino annihilations. In each case we present the allowed region for (a) the original parameter space; (b) the chargino mass $M_{\chi_1^+}$ versus the neutralino mass $M_{\chi_1^0}$; (c) the cross section of chargino pair production at LHC and ILC versus the chargino mass $M_{\chi_1^+}$. Note that we just give the tree-level cross sections and do not include the one-loop corrections [15]. The center-of-mass energy is 14 TeV for LHC and is assumed to be 1 TeV for ILC [16]. The results are resented in Figs. 2-5, where the dot-dashed line is the LEP II lower limit on chargino mass.

(1) $M_1 = M_2/2$: This case is well motivated since the supergravity models predict the unification relation $M_1 = \frac{5}{3} M_2 \tan^2\theta_W \simeq 0.5 M_2$. In the low mass region for both M_2 and μ in Fig. 2(a), the dark matter is the mixing of gauginos and Higgsinos. The strip with very large M_2 corresponds to Higgsino dark matter, while the strip with very large μ corresponds to gaugino dark matter (the mixing of bino and wino). From Fig. 2(b) we see that both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ is upper bounded by about 1 TeV. Fig. 2(c) shows that in the allowed region the cross section of chargino pair production at LHC can reach a few pb for a light chargino, but

drops rapidly as the chargino gets heavy. The cross section at ILC can reach 100 fb for a light chargino in the allowed region.

(2) Superheavy μ: This case was proposed and favored by some authors [17] because the μ problem [18] is avoided and a crude gauge coupling unification is preserved. In the low mass region for both M_2 and M_1 in Fig. 3(a), the dark matter is the mixing of bino and wino; while the region with large M_1 corresponds to wino dark matter. Fig. 3(b) shows that both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ is upper bounded by about 3 TeV. Fig. 3(c) shows that in the allowed region the cross section of chargino pair production at LHC can reach 10 pb for a light chargino, but drops rapidly as the chargino gets heavy. The cross section at ILC can reach 200 fb for a light chargino in the allowed region.

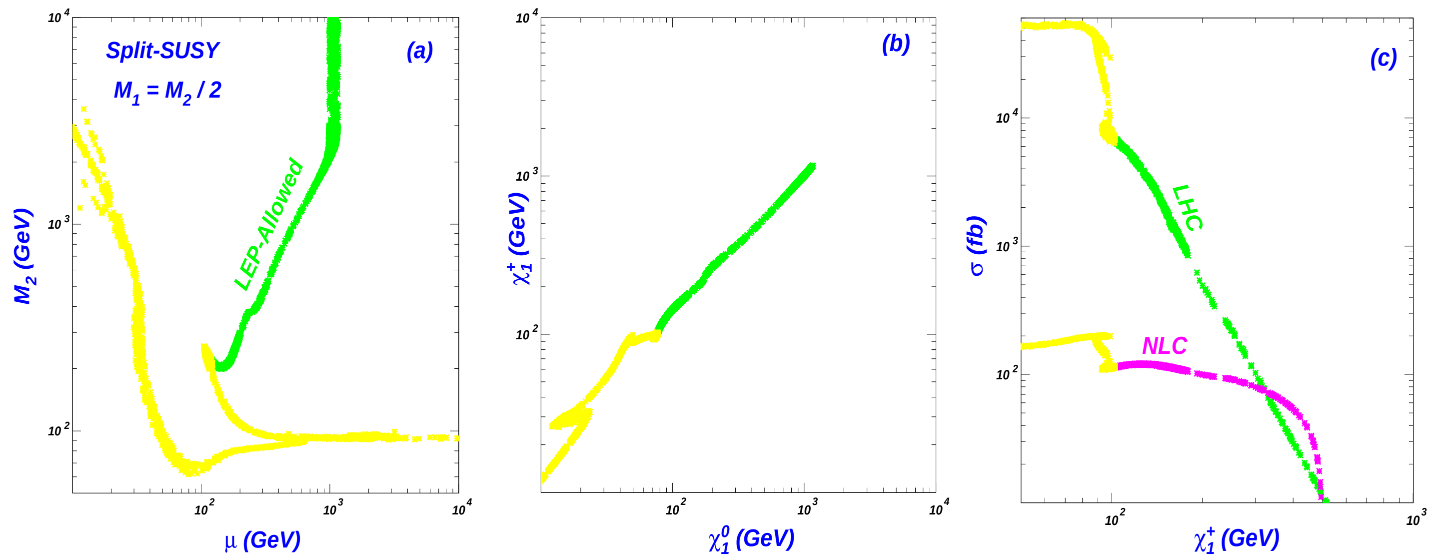

FIG. 2. The WMAP 2σ allowed region (shaded area) in case of $M_1 = M_2/2$. The light shaded region (yellow) is not allowed by LEP experiment.

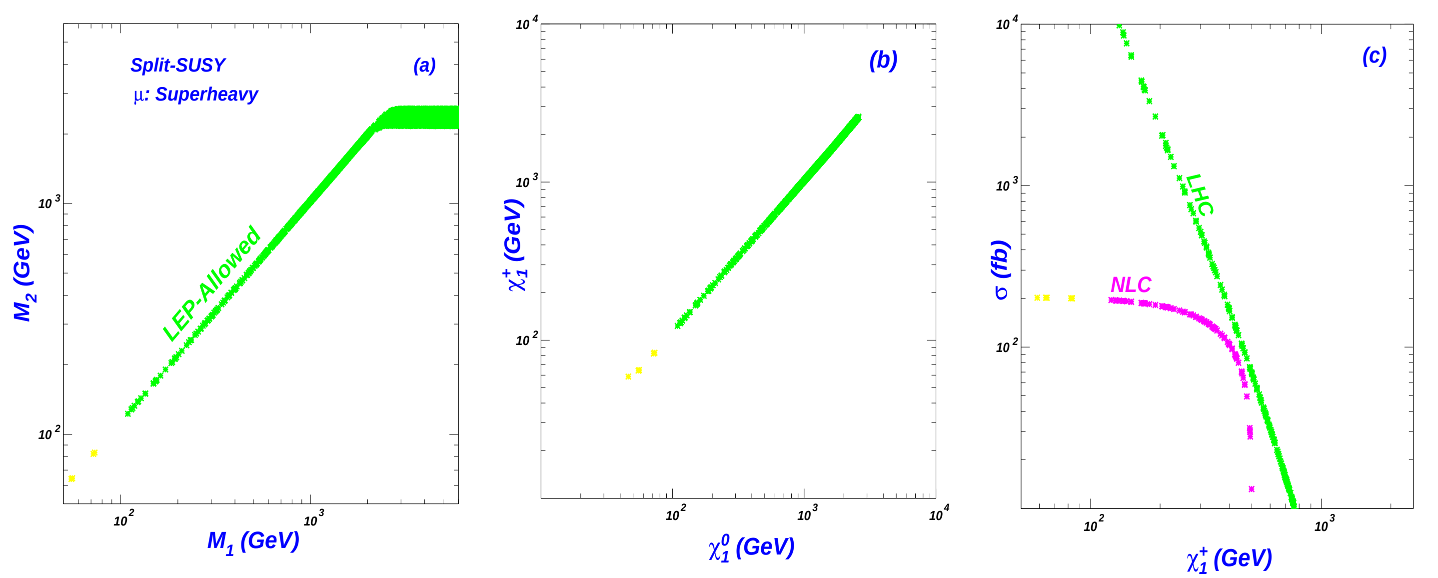

FIG. 3. The WMAP 2σ allowed region (shaded area) in case of superheavy μ. The light shaded region (yellow) is not allowed by LEP experiment.

(3) Superheavy M_2: In the low mass region for both M_1 and μ in Fig. 4(a), the dark matter is the mixing of bino and Higgsinos. When M_1 (μ) gets very large, a strip is remained, which corresponds to Higgsino (bino) dark matter.

The chargino mass $M_{\chi_1^+}$ is upper bounded by about 3 TeV and the neutralino mass $M_{\chi_1^0}$ is upper bounded by about 1 TeV. For a light chargino in the allowed region, the cross section of chargino pair production can reach the level of pb at LHC and 100 fb at ILC.

(4) Superheavy M_1: In Fig. 5(a) the strip with large M_2 (μ) corresponds to Higgsino (wino) dark matter. As shown in Fig. 5(b), both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ are lower bounded by about 1 TeV and upper bounded by about 2.5 TeV. Thus the charginos cannot be pair produced at the ILC with c.m. energy of 1 TeV. Although the charginos can be pair produced at the LHC, the cross section is very small, as shown in Fig. 5(c).

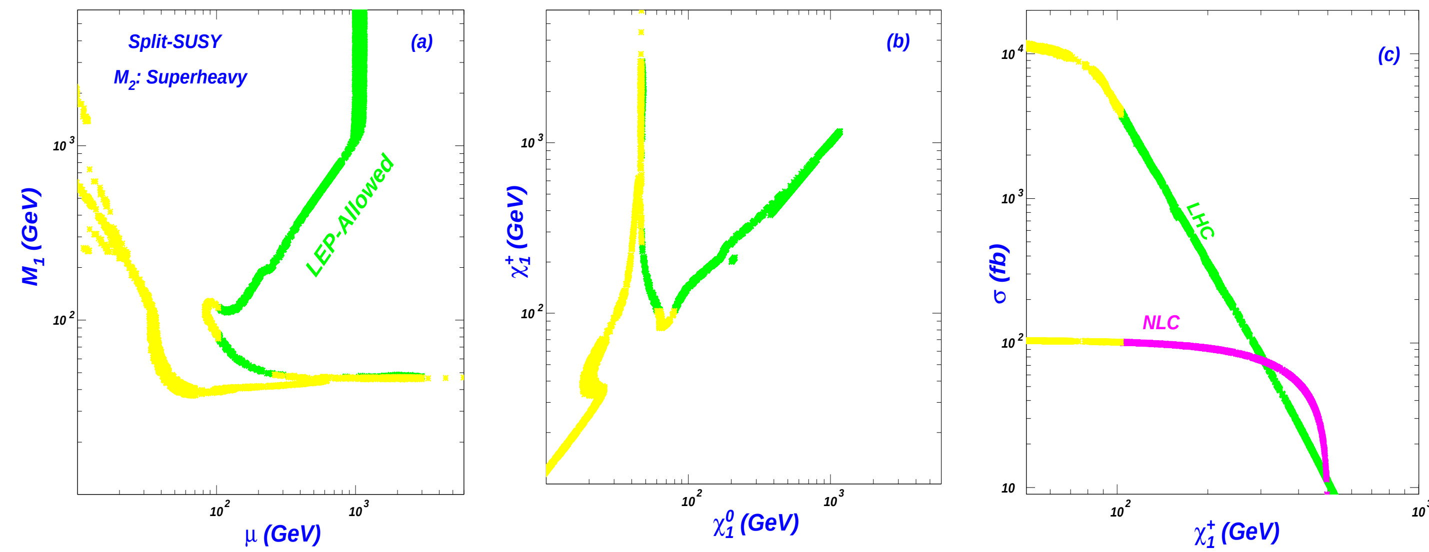

FIG. 4. The WMAP 2σ allowed region (shaded area) in case of superheavy M_2. The light shaded region (yellow) is not allowed by LEP experiment.

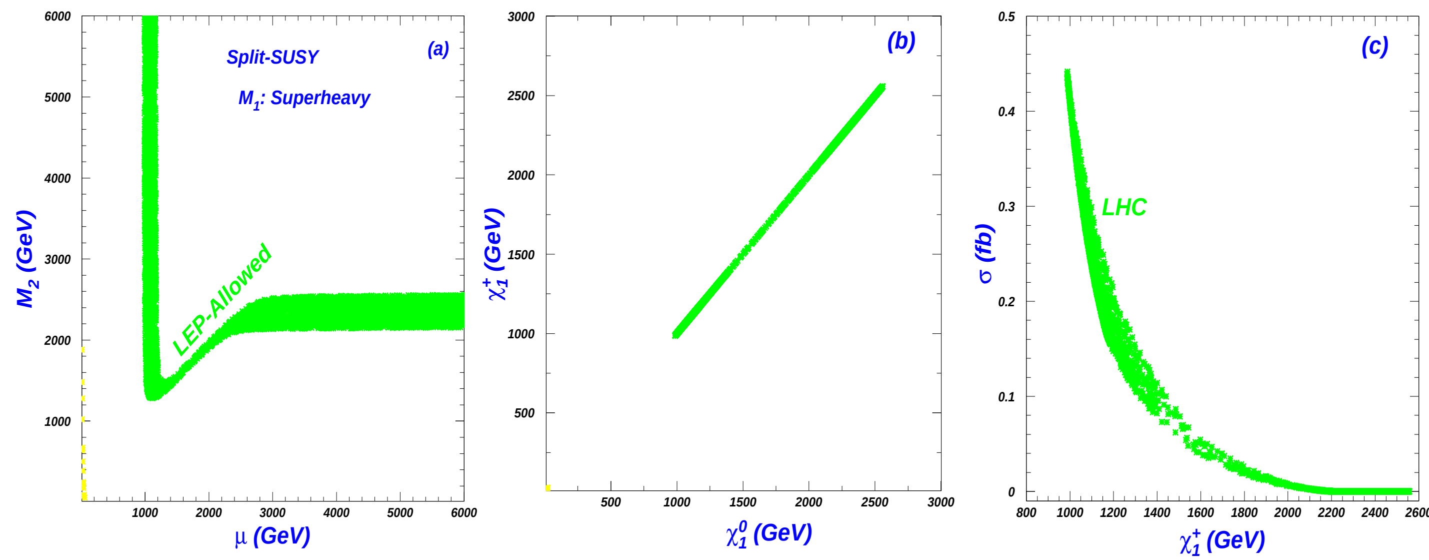

FIG. 5. The WMAP 2σ allowed region (shaded area) in case of superheavy M_1. The light shaded region (yellow) is not allowed by LEP experiment.

Note that while the chargino pair production with a rate of 100 fb at ILC may not be hard to observe due to the clean enviroment of the ILC (chargino pair production is regarded as a good way to test split supersymmetry at ILC [19]), searching for the chargino pair production with a cross section of pb level at the LHC may be quite challanging. The chargino χ_1^+ decays into a neutralino χ_1^0 and a pair of fermions (two jets or a charged lepton plus a neutrino). So

the signature of chargino pair production is (i) two energetic leptons plus missing energy, or (ii) one energetic lepton plus two jets plus missing energy. Let us take the latter signature, i.e., $\ell + 2j + P_T^{\rm miss}$, as an example. The huge background comes from Wjj. In order to substantially reduce this background, we may apply a cut on the transverse mass defined by

$$m_T = \sqrt{(P_T^\ell + P_T^{\rm miss})^2 - (\vec{P}_T^\ell + \vec{P}_T^{\rm miss})^2}. \tag{3.2}$$

m_T is always less than M_W (and peaks just below M_W) if the only missing energy comes from a neutrino from W decay, which is the case for the Wjj background events. For the signal, m_T is spread about equally above and below M_W, due to the large extra missing energy from the neutralinos. Therefore, we may, for example, require $m_T > 90$ GeV. Given the importance of chargino pair production as a test of split supersymmetry at the LHC, detailed Monte Carlo studies with the consideration of various backgrounds are needed, which is beyond the scope of this work.

IV. CONCLUSION

In split supersymmetry, gauginos and Higgsinos are the only supersymetric particles which are possibly accessible at the LHC or the ILC collider. The masses of these particles are subject to the stringent constraints from the cosmic dark matter. Under the assumption that the lightst neutralino is the LSP and constitute the dark matter in the universe, we scrutinized the dark matter constraints on the masses of charginos and neutralinos. We considered several cases: (1) $M_1 = M_2/2$; (2) μ is superheavy; (3) M_2 is superheavy; and (4) M_1 is superheavy. We found that the lightest chargino χ_1^+ must be lighter than about 1 TeV in the first case and about 2 or 3 TeV in other cases. In the first three cases, the corresponding production rate of the chargino pair at the LHC (ILC) can reach the level of pb (100 fb) in some parts of the allowed region and thus hopefully observable. But in the last case, the chargino must be heavier than about 1 TeV and thus has a too small production rate to be observale at the LHC. So, overall, there is no guarantee to find the charginos of split supersymmetry at the LHC or ILC collider.

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